Mass Requirements for Helicopter Aircrew Helmets

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1. SUMMARY

Helicopter aircrew helmets are becoming more sophisticated with increased mission requirements. This increase results in additional mass being supported on the aircrew's head. Ultimately, there is a limit to how much mass can be supported by the aircrew without increasing the fatigue rates and neck injury risk in accidents. This paper reviews the past mass property requirements of Army helicopter helmets. Current requirements for the RAH-66 Comanche helmet are also detailed with the rationale for their derivation.

2. LIST OF SYMBOLS

AH-64	Attack helicopter
CM	Center of mass
cm	Centimeter
HMD	Helmet mounted device
HSD	Head supported device
IHADSS	Integrated helmet and display sighting system
kg	Kilogram
kg-cm	Kilogram-centimeter
M	Moment
m	Mass
N	Newtons
N-cm	Newton-centimeter
NVG	Night vision goggle
PM	Program manager
PNVS	Pilot night vision system
RAH-66	Reconnaissance attack helicopter
SPH-4	Sound protective helmet #4

3. SUBJECT MATTER KEYWORDS

Aircrew
Helmets
Protective headgear
Mass
Mass requirements
Mass properties
Center of mass
Center of gravity
Head supported devices
Helmet mounted devices

4. INTRODUCTION

The mass of the flight helmet used by fixed-wing and rotary-wing pilots has been a concern since "hard shell" helmets first appeared in the 1950s. These helmets were introduced to provide increased head protection during a crash, but at a significant weight increase over the previously worn cloth caps. The total headborne mass increased from 0.5 kg for the leather or cloth cap to 1.5 kg for early hard shell helmets which included noise-attenuating earcups, earphones, microphone, and integral, adjustable visors. The hard shell helmet, lined with polystyrene foam, provided an order of magnitude improvement in impact protection.

In the 1980s, the introduction of various visual enhancement devices further increased the mass to 3 kg for the standard Army sound protective helmet No. 4 (SPH-4) equipped with the pilot night vision system No. 5 (PNVS-5). The increased mass of this helmet system is believed to have a detrimental effect on pilot performance due to neck muscle strain and fatigue and, also, to increase the risk of severe neck injury in crashes. The disadvantages of increased helmet mass, however, are offset by the enhanced visual capability for night flying and increased weapons aiming capability offered by helmet-mounted image intensification devices and other helmet-mounted displays. In order to permit the use of 3 kg helmets without overloading the neck in severe crashes, the U.S. Army's night vision laboratory at Fort Belvoir, VA, developed a spring-loaded, ball-socket mount which permits the latest generation night vision device (AN/AVS-6) to break free during a crash. The 0.6 kg night vision goggle (NVG) device was designed to break free of the helmet at a goggle deceleration of 10 to 15 times the acceleration of gravity (G) (Military specification, MIL-A-49425(CR))[1]. Although this approach may offer one solution to the problem of increased head-supported mass in Army aviation, little is known about the dynamic behavior of this device in a crash or of the physical limitations of the human neck to support these masses.

In an initial attempt to define a safe limit on flight helmet mass for the Army, the United States Army Aeromedical Research Laboratory (USAARL) in 1982 proposed a limit of 1.8 kg (3.96 lb) during the development of the AH-64 Apache flight helmet [2]. The helmet system subsequently developed met this mass limitation while providing the desired visionics and required impact protection. Nonetheless, the SPH-4 helmet with NVG attached used for night operations in all other Army helicopters continued to exceed the proposed 1.8 kg limit by more than a full kilogram. Although there have been anecdotal reports from aviators complaining of considerable discomfort with this system, particularly after long missions, the effects on pilot performance of bearing this much mass has never been systematically studied. Furthermore, the dynamic consequences of crashing with head-borne masses approximating 3 kg remain largely speculative.

5. BACKGROUND

5.1 Helicopter helmet functions

The functional requirements of the helicopter pilot helmet have grown considerably. Traditional helmet functions include head impact protection and service as a mounting platform for communication systems, hearing protection, eye protective visors, and on occasion, oxygen systems. Increases in threats and operational effectiveness demand the helmet also serve as a mounting platform for such systems as weapon targeting, night vision or image intensification devices, flight symbology displays, chemical

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defense masks, and nuclear flash protection. These requirements demand more complex mounting devices on the helmet and, ultimately, result in increased system weights and potentially less than optimal center of mass (CM) placement.

5.2 Prior helmet mass requirements

Historically, helmet mass and CM requirements have been nonexistent or vague. These requirements were often loosely written and based on existing designs. Language in helmet development specifications often resembled "the helmet CM must be located as close to the head CM as possible," "lighter and CM no worse than current helmet systems," "provide ease of head movement," and "reduced bulkiness." These requirements provided little guidance to the design teams and could not be quantitatively evaluated.

5.3 Mass properties

Seven parameters are required to fully define the mass properties of helmet systems. As illustrated in Figure 1, these include mass, the center of mass position along three orthogonal axes, and the mass moment of inertia about the three respective axes. The coordinate system used by the Army aviation community is based on the head anatomical coordinate system and is illustrated in Figure 2 [3]. The x-axis is defined by the intersection of the mid sagittal and Frankfort planes with the positive direction anterior of the tragion notch. The y-axis is defined by the intersection of the Frankfort and frontal planes with the positive y-axis exiting through the left tragion notch. The z-axis is oriented perpendicular to both, the x- and y-axes following the right hand rule.
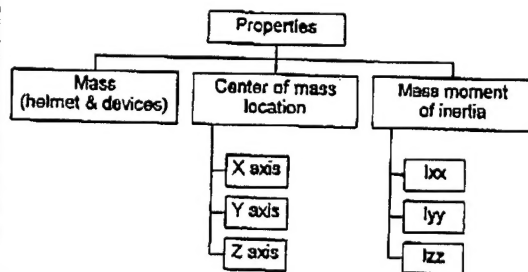

Figure 1. Parameters required to fully define helmet system mass properties.

5.4 The need for mass property requirements

The reason for defining aviator helmet mass requirements can be segregated into three areas; aircrew health, operational effectiveness, and user acceptance. Aircrew health can be affected by both short- and long-term exposures of head and neck loadings. Long term exposures are the result of helmet mass and its mass center location in normal flight conditions (vibration and 1 to 2 G flight environment). These effects include discomfort from a sore or stiff neck after normal missions. It is not uncommon to find Army aircrew who admit "off-the-record" that they seek unauthorized treatment for sore neck muscles. Treatments may include heat pads, topical ointments, neck rubs and massages from spouses or masseuses, and chiropractic adjustments.

Short-term exposures may cause neck injuries resulting from inertial loadings. Inertial neck loadings are created in
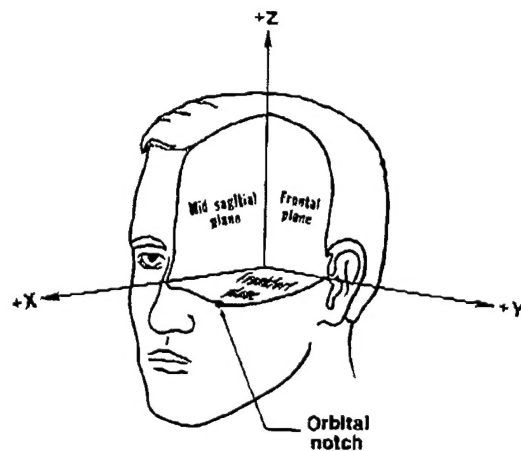

Figure 2. Head anatomical coordinate system.

high acceleration, short duration, dynamic crash environments. At high seat accelerations, neck loads are compounded by helmet mass and improper center of mass locations. These neck injuries can be low severity, such as strains and muscle tears, or high severity, such as cervical transections.

Aircraft crash environments also may cause direct and indirect loading injuries to the neck. Direct loading injuries are caused by objects physically striking the neck inflicting tissue damage. Indirect loading neck injuries are caused by the transfer of energy to the neck from a head impact. It is assumed that neither direct nor indirect loading neck injuries are influenced by the mass supported by the head. Thus, these direct and indirect types of neck injuries are not considered in the determination of allowable mass properties for head supported devices.

The mass properties of head supported devices (HSD) also can affect operational effectiveness by increasing aircrew fatigue. Aircrew operating with high fatigue are less efficient, have lower mental concentration ability, and are more prone to commit mistakes. Little data is available on fatigue effects in rotary-wing environments and is generally based on small sample sizes and limited helmet mass and CM positions.

Helmet stability also is affected by helmet mass and CM placement. High helmet mass and misplaced center of mass locations can result in helmet slippage relative to the aircrew eye location. When helmet-mounted displays or image intensification devices are used, helmet slippage could effectively "blind" the aviator from receiving the desired display information for effective aircraft control.

The final area which can be affected by head-supported mass is user acceptance. The final configuration must be acceptable to the final user prior to fielding to operational units. Failure of a system to receive user acceptance will result in misuse and abuse of the system and failure of the system to achieve its desired operational capability. User acceptability is difficult to define and quantify since each aircrew has a subjective opinion. No data beyond anec-

dotal data on existing systems has been generated to quantify user acceptance of mass property limits.

6. APPROACH

The USAARL was asked to review head-supported weight requirements by the Program Manager, Comanche (PM-Comanche) of the Army Aviation and Troop Command (ATCOM) in St. Louis, MO. As a result of this review, a series of memoranda were submitted to PM-Comanche recommending changes to the mass property requirements of head-supported devices. Recommendations were made by USAARL to change the total allowable mass and the x-and z-axes CM locations. The recommended allowable mass requirement were based on neck tensile strength. The x-axis CM location was based on measured biodynamic responses of aviators wearing various helmet mass and CM combinations. The z-axis CM was based on maintaining a constant moment about the C7/T1 juncture resulting from the helmet mass and vertical CM position.

7. ANALYSIS

7.1 Inertia loading-neck injury mechanisms

It is important to define the mechanisms of neck injury when establishing mass limits on HMDs. McElhanney provides a good engineering description of neck loadings, which are reproduced in Figure 3 [4]. Two injury mechanisms are most likely to be affected by the mass properties of HMDs. These are axial tension and forward bending (flexion). Neck extension and neck compression injury mechanisms are not considered to be effected by HMD mass properties. This is based on current helicopter crew seat design requirements which include headrest and load limiting vertical energy absorption capabilities.

Shanahan and Shanahan, in a study of U.S. Army helicopter crash injuries from 1979-1985, found 82 reported spinal fractures [5]. Figure 4, taken from the Shanahan report illustrates the spinal fracture distribution by vertebral level. The cervical and upper thoracic vertebra with the highest frequency of fracture was the 7th cervical. The lower thoracic and the lumbar region experienced a higher frequency rate, but these injuries are believed due to compression loadings resulting from high vertical impact loads in precrashworthy seat designs. Cervical spine fractures comprise only 1.6 percent of the 1484 injuries sustained in survivable crashes. The cervical injuries were caused by either acceleration loadings or contact injury. No differentiation between these two injury mechanisms was made.

This review of helicopter crash injury indicates a lack of evidence supporting significant inertial neck injury for Army aviators wearing a 1.5-1.8 kg helmet. In some crashes, heavier helmets of 2.9 kg (including night vision components) have been worn, but the extra 1.1 to 1.4 kg mass of night vision goggles and counterbalance weights have broken free from the helmet and relieved the neck of this added loading. The non-documentation of inertial neck injury does not mean none occurred, but that the accident investigators failed to recognize this infrequent injury among the far more obvious contact, crushing, and spinal column injuries in the older, non load-limiting seats.
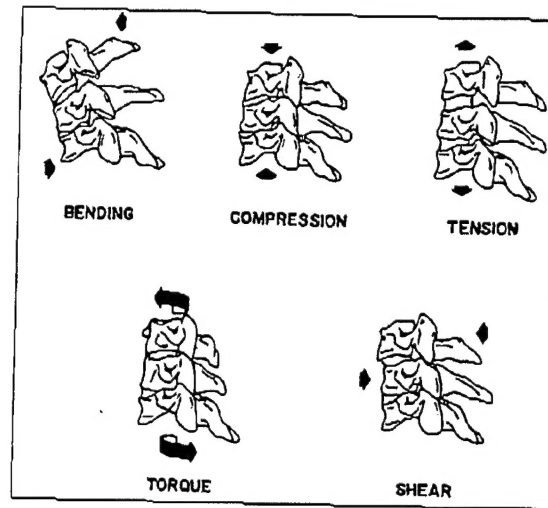

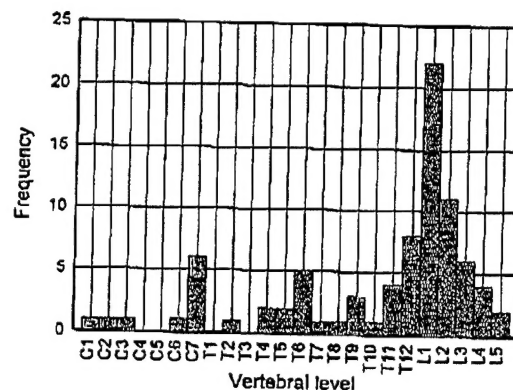Figure 3. Engineering descriptions of neck loading.

Figure 4. Frequency distribution of spinal fractures in class A and B survivable crashes as vertebral level.

7.2 Factors influencing inertial neck injury

Recent Army helicopter designs incorporate minimal levels of crashworthiness with specific performance levels for the crewseats. Helicopter crew seats are typically procured to military performance specifications with a 30G longitudinal static load requirement and a vertical energy absorption capability (Military specification, MIL-S-58095(AV)). [6] The 30 G longitudinal requirement is a structural integrity check of the seat and its mounting hardware to provide assurance that the seat will not be ripped from the floor. The vertical energy absorber is a mechanical device which restricts the vertical crashloads experienced by the occupant. The desired vertical load is an average of 14.5 G over the range of seat stroke. Peak loads of 18.3 G have been measured in anthropomorphic test dummies during seat qualification trials [7]. The worst case condition would be a seat experiencing 30 G longitudinally and stroking with a peak vertical load of 18.3 G. The resultant from these two loading vectors is 35 G directed 31.4 degrees downward from horizontal.

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Aircrew restraint systems utilized in Army helicopters are either a traditional 4-point restraint system or a newer 5-point restraint. The primary difference between the two systems is that the 5-point system includes a center tie-down strap to reduce occupant submarining (movement of the pelvis under the lap belt). Dynamic tests with rigid seat structures have indicated a range of possible "dynamic overshoot" (the ratio of measured head or chest acceleration of a test dummy to the input floor or seat acceleration). This increase in acceleration results from harness slack, neck tissue stretch, and upper body compression (by contact with restraint harness) which allows a relative velocity to be created between the occupant and surrounding structure. The dynamic overshoot value is also dependent on when the shoulder strap inertia reel locks (which is activated by occupant motion). A dynamic overshoot value of 1.5 has been selected as the magnification of seat acceleration to the head acceleration; this is an average value based on dynamic tests of aircrew seats for the UH-60 Black Hawk helicopter.

7.3 Neck strength
A literature search was conducted to assess neck strength. This review (report is in draft form for USAARL publication) revealed data from military operational experiences [8], automotive accident injuries [9,10], volunteer [11,12], and cadaver test data [13,14], animal test data [15], and manikin injury assessment values [16]. Based on our analysis of this data, a neck tensile strength threshold of 4050 Newtons was selected as the maximum limit. It is believed that risk of serious neck injuries exist above this limit for the Army aviator population. This value is probably too great for populations other than military aviators since aviators generally are young and physically fit.

8. MASS PROPERTY LIMIT DETERMINATION

8.1 Mass requirements
The determination for maximum allowable HSD mass is based on Newton's second law; $F = ma$. This equation is used by considering the neck tensile strength threshold of 4050 Newtons and the acceleration environment of 35 G with a dynamic overshoot ratio of 1.5. The effective mass acting on the C7/T1 juncture can then be calculated as follows:

$$F = ma$$
$$m = F / a$$
$$m = 4050 / [(35) * (1.5) * (9.81)]$$
$$m = 7.86 \text{ kg}$$

The mass acting on the C7/T1 juncture includes the helmet, head, and neck. The total mass of the neck is included in this calculation to be conservative. By subtracting the head mass (4.32 kg) and neck mass (1.04 kg) from the above value, we arrive at the allowable helmet mass for the given impact condition.

$$m = m_{head} + m_{neck} + m_{helmet}$$
$$m_{helmet} = m - m_{head} - m_{neck}$$
$$m_{helmet} = 7.86 - 4.32 - 1.04$$
$$m_{helmet} = 2.5 \text{ kg}$$

8.2 Vertical CM requirements
The vertical center of mass limit is based on a constant mass moment concept acting about the C7/T1 juncture. This rationale allows for greater helmet mass as the vertical CM location moves downward. The C7/T1 juncture was selected as the pivot point because, as noted by Shanahan [5], it is more frequently injured in helicopter accidents than upper cervical vertebra. Application of this theory requires selection of a HSD mass and vertical CM position to use as a constant mass moment. Lack of emperical data necessitated the selection of the "worst case" fielded helmet system, the AH-1 cobra helmet configuration, to establish an acceptable constant mass moment. This helmet configuration has a mass of 1.74 kg and a vertical CM location of 5.2 cm above the tragion notch. The final variable needed to determine the constant mass moment is the vertical distance between the C7/T1 juncture to the tragion notch [17]. A value of 11.94 cm was selected which represents the 95th percentile female and the 85th percentile male.

To determine the constant mass moment, the definition of a mass moment is used: $M = md$. The mass is the helmet mass of 1.74 kg and the distance is the total distance of the helmet vertical CM position above the C7/T1 juncture (11.94 cm + 5.2 cm). This is calculated as follows:

$$M = md$$
$$M = (1.74) * (11.94 + 5.2)$$
$$M = 29.8 \text{ kg-cm}$$

This moment value can be used to establish a relationship between the vertical CM position and mass by rearranging the above equation as follows:

$$29.8 = m_{helmet} * (11.94 + Z_{helmet \, cm})$$
$$Z_{helmet \, cm} = (29.8 / m_{helmet}) - 11.94$$

Plotting this relationship results in the curve shown in Figure 5. The allowable mass is limited to 2.5 kg as determined above. Additionally, the allowable vertical CM position is limited to 5.2 cm since biodynamic reactions to higher CM locations are unknown. Plotting specific HSD mass and vertical CM values on the graph allows acceptability assessment.
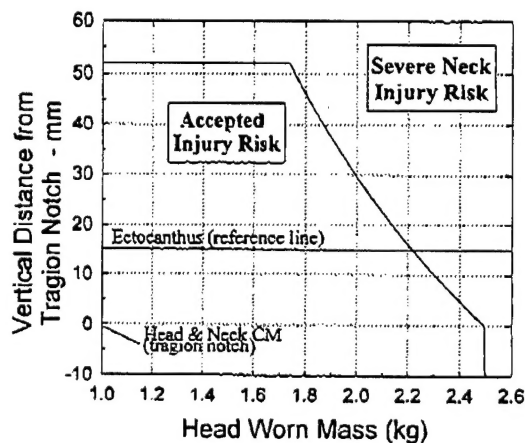

Figure 5. Vertical center of mass placement as a function of head worn mass.

8.3 Longitudinal CM requirements

The longitudinal CM locations of HSDs are believed to have greater effects on wearer fatigue and performance decrements than crash induced injury. Efforts have been conducted by Butler [18] to assess these effects by exposing volunteers to controlled helicopter ride environments with various helmet mass and CM configurations. During his study, Butler measured both physiological and biomechanical responses to the changes in HSD mass properties. The property changes included three masses (2, 3, & 4 kg) and four longitudinal CM positions (-2, 0, 2, & 4 cm) measured relative to the head center of mass. A head supported weight moment of 82.8 ± 22.8 N-cm, measured about the occipital condyles, was recommended based on changes in head pitch accelerations and posterior neck myoelectric responses. It was also recommended that negative moments be avoided. By using the recommended weight moment, including the tolerance (105.6 N-cm total), this value can be converted into a mass moment relative to the tragion notch and plotted. This relationship is shown in Figure 6. The rearward CM location was limited at -2 cm based on Butler's recommendation [18] that negative moment be avoided. Mass was limited at 2.5 kg as determined earlier. The forward limit was arbitarly set at 9.5cm.
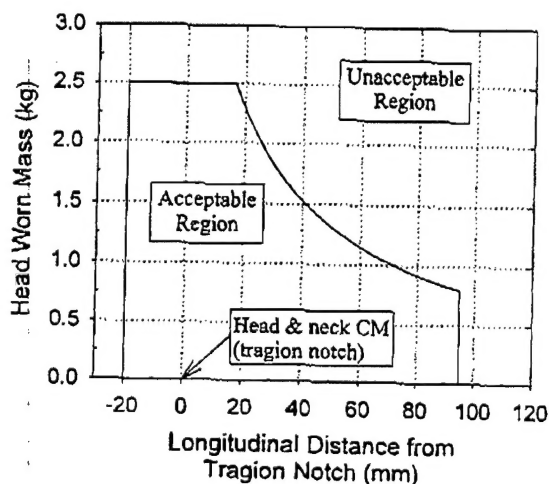

Figure 6. Allowable head-worn mass as a function of longitudinal center of mass placement.

8.4 Lateral CM requirements

No data has been identified to warrant changing the lateral CM requirements from 1.9 cm off the mid-sagittal plane. Operationally, the IHADSS helmet, which is used in the AH-64 Apache helicopter, possesses an off sagittal CM position when the monocular helmet-mounted display is attached. No neck injuries to the occupants involved in mishaps have been attributed to the lateral CM locations. This may be attributed to the breakaway capability of the HDU when exposed to contact forces and high accelerations.

9. RECOMMENDATIONS

The mass and center of mass requirements presented are based on limited data. Future efforts should be expended to increase the available human tolerance data and subsequently refine or change the presented mass requirements. These efforts should include defining human neck strength to various loading mechanisms, defining user tolerance to mass properties of head-supported devices, and defining fatigue affects of HSD mass properties. Epidemiological studies should be conducted to determine the incidence of chronic neck injury among aging and retired aircrew and its correlation to flight experience. Finally, numerical simulations of occupant loads in crash situations should be conducted to validate the presented HSD mass requirements.

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